

Gyrokinetic Simulation of Turbulence Transport with Kinetic Electrons and Electromagnetic Perturbations

Yang Chen

Center for Integrated Plasma Studies
University of Colorado at Boulder

In collaboration with: S. E. Parker, B. I. Cohen, A. M. Dimits, W. M. Nevins,
D. Shumaker, V. K. Decyk and J. N. Leboeuf (Summit Team)

Work supported by DOE SciDAC Plasma Microturbulence Project

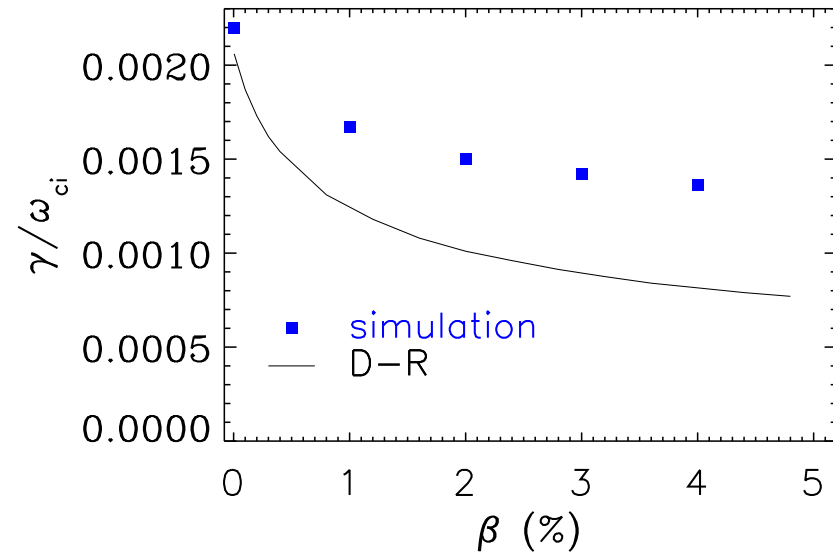
Outline

- The “High- β Problem” and Solution
- General Observations from Nonlinear Simulations
- Effect of β on ITG Turbulence and Transport
- Summary and Future Work

The “High- β Problem”

$$\left(-\nabla_{\perp}^2 + \beta \frac{m_i}{m_e}\right) A_{\parallel} = -\beta u_{\parallel e}$$

- First observed by Cummings ('94)
- Does not appear in implicit Eulerian codes (Kotschenreuther et. al. '95; Dorland et. al. GS2, '00)
- Solved in explicit Eulerian codes (Hammett, Jenko, '01 PMP mtg; Candy and Waltz, GYRO, '02)



$$\nabla \times \widetilde{\mathbf{B}} = \mu_0 j_{\parallel e}$$

$$\longrightarrow \quad \left(-\nabla_{\perp}^2 + \beta \frac{m_i}{m_e} \right) A_{\parallel} = -\beta u_{\parallel e}$$

$$\int f_0(p_{\parallel}) v_{\parallel} dv = \frac{m_i}{m_e} A_{\parallel}$$

$$\beta \sim 1\%, \text{ for ITG modes } \nabla_{\perp}^2 \sim 0.01, \beta \frac{m_i}{m_e} \sim 20.$$

A very stiff problem!

Key Elements of the New Algorithm

- Use canonical momentum $p_{\parallel} = v_{\parallel} - \frac{e}{m_e} A_{\parallel}$. (Hahm et. al. '88)

– to eliminate $\frac{\partial A_{\parallel}}{\partial t}$

$$E_{\parallel} = -\nabla_{\parallel}\phi - \frac{\partial A_{\parallel}}{\partial t}$$
$$m_e \frac{dp_{\parallel}}{dt} = -eE_{\parallel} - e(v_{\parallel}\nabla A_{\parallel} + \frac{\partial A_{\parallel}}{\partial t})$$

- δf method with $\delta f = f_e - f_0(p_{\parallel})$
- Split-weight Scheme (Manuilskiy and Lee '00, Chen and Parker '01)
 - to increase Δt
- New algorithm for Ampere's equation

$$(-\nabla_{\perp}^2 + \beta \frac{m_i}{m_e}) A_{\parallel} = -\beta u_{\parallel e} \quad \nabla_{\perp}^2 \sim 0.01, \quad \beta \frac{m_i}{m_e} \sim 20$$



$$\int f_0(p_{\parallel}) v_{\parallel} dv_{\parallel} \quad \text{why not } f_0(v_{\parallel})?$$

SOLUTION

$$u_{\parallel e}(\mathbf{x}) = \sum_j w_{ej} p_{\parallel j} S(\mathbf{x}_j - \mathbf{x})$$

w_{ej} – electron weight

S – the particle shape function

The evaluation of the “zero-order” electric current mimics that of the perturbed current, so that effects of particle shape and finite particle number to both currents offset each other.

$$\frac{m_i}{m_e} A_{\parallel} \approx \frac{V}{N} \sum_j p_{\parallel j}^2 A_{\parallel}(\mathbf{x}_j) S(\mathbf{x} - \mathbf{x}_j)$$

$$A_{\parallel}(\mathbf{x}_j) = \sum_{l,m,n} A_{\parallel}(\mathbf{x}_{l,m,n}) S(\mathbf{x}_j - \mathbf{x}_{l,m,n}),$$

interpolated from A_{\parallel} at nearby grids

Suppose $f_e = f_0(v_{\parallel}) = f_0(p_{\parallel}) + w$.

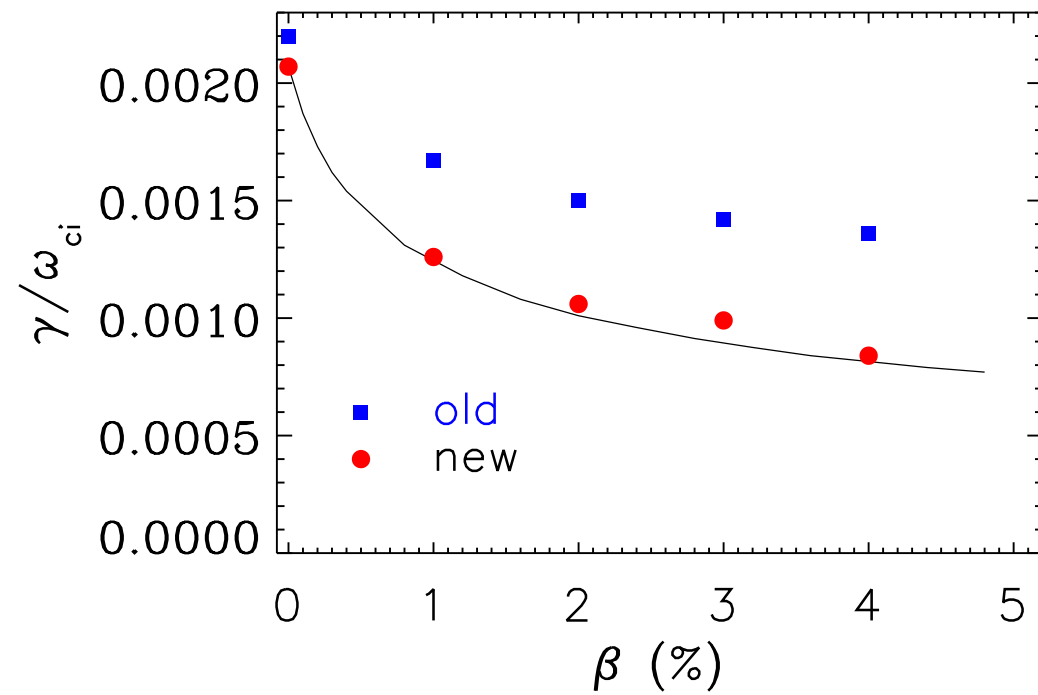


electron weight

$$w = f_0(v_{\parallel}) - f_0(p_{\parallel}) \approx -\frac{1}{T}p_{\parallel}A_{\parallel}f_0(p_{\parallel})$$

$$e^{-m_e(p_{\parallel} + \frac{1}{m_e}A_{\parallel})^2/2T}$$

$$w \sim p_{\parallel}A_{\parallel}$$

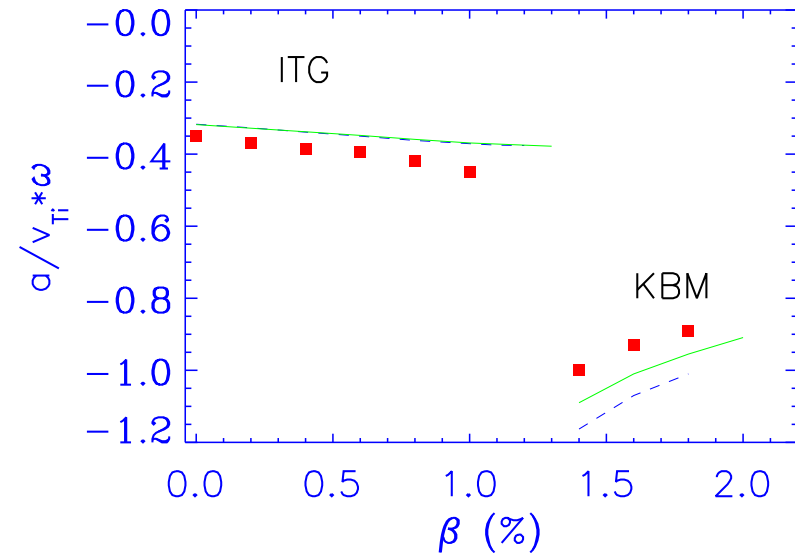
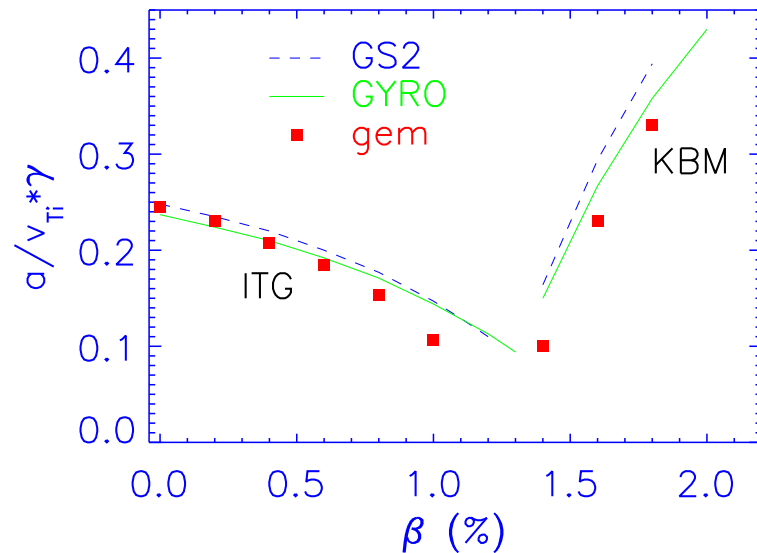


- Finite β effect on slab ITG
- Alfvén wave frequency also accurate for $\beta \sim 10\%$

Current Features of SUMMIT Framework

- Flux-tube using field-line-following coordinates (Beer '95)
- Nonshifted, circular equilibrium
- Passing + trapped kinetic electrons
- Lorentzian electron-ion collisions
- Domain decomposition in z with cloning (C. Kim and S. Parker, '00)
- Parallel nonlinearity $E_{\parallel} \frac{\partial \delta f}{\partial v_{\parallel}}$
- Field-solving comparable to particle-pushing
- Work underway to merge with codes using quasi-ballooning coordinates in general geometry (Leboeuf, Dimits, Shumaker)

Linear Benchmark with Continuum Codes Shows Good Agreement

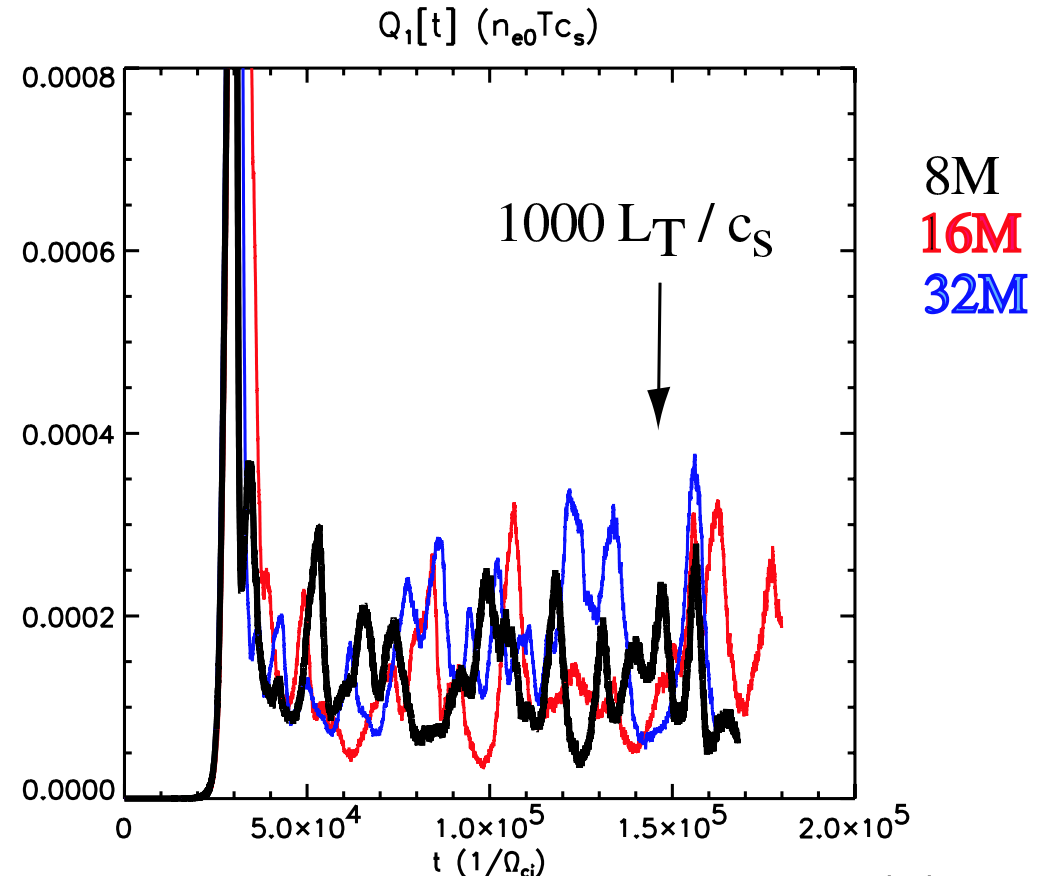


- $k_y \rho_i = 0.3$. Deuterium plasma with $R_0/L_T = 9$, $\eta_i = 3$,
 $q = 2$, $\hat{s} = r q' / q = 1$

Candy and Waltz, JCP 186(2), 545 (2003)
Dorland, 18th IAEA (2000)

Convergence Test

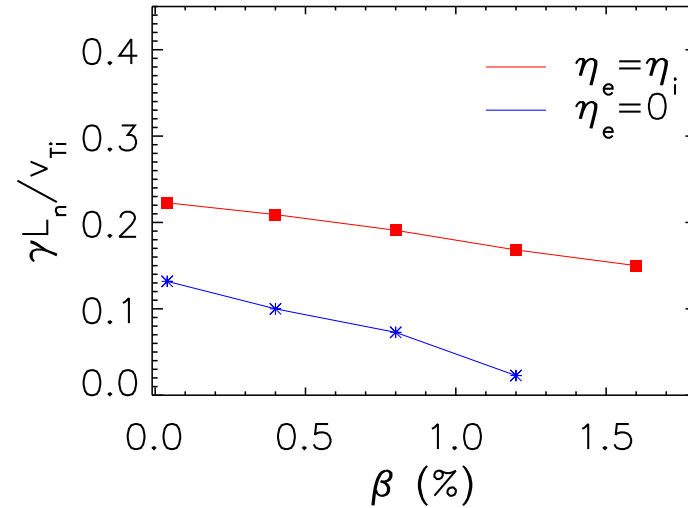
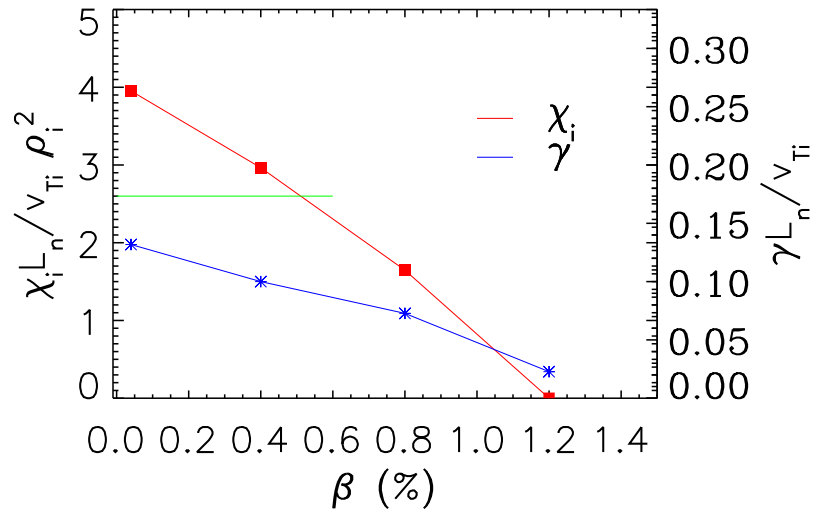
- $\beta = 0.8\%$, $m_i/m_e = 400$
- $L_x = L_y = 64\rho_i$, $N_x = N_y = 64$, $N_z = 32$
- $k_y\rho_i \leq 0.8$
- Convergence achieved with 32 particles per species per cell
- Converged w.r.t. box size $64\rho_i \times 64\rho_i \longrightarrow 128\rho_i \times 128\rho_i$, for low β , $\frac{m_i}{m_e} = 1837$



Some Observations from Nonlinear Simulations

- Cyclone Base Case $R/L_T = 6.9$, $R/L_n = 2.2$, $q = 1.4$, $\hat{s} = 0.78$ (shot #81499, t=4000ms)
- Nonlinear Landau damping ($E_{\parallel} \frac{\partial \delta f}{\partial v_{\parallel}}$) reduces χ_i by $\sim 30\%$ for $\beta = 0.8\%$
 - Consistent with Jenko and Scott, '98
- From $\frac{m_i}{m_e} = 1837$ to $\frac{m_i}{m_e} = 400$ χ_i increases significantly.
- Simulations with finite $\eta_e = \eta_i$ does not show significant contribution to χ_e from magnetic fluttering $\langle v_{\parallel} \tilde{B}_r \delta f \rangle$
- At $\beta \frac{m_i}{m_e} > 1$, with periodic radial boundary condition, large radial box size leads to large saturation amplitude of the fundamental mode $k_y = \frac{2\pi}{L_y}$ and strong correlation across radial boundaries.
 - disappear with nonperiodic b.c.
- β -dependence of χ_i sensitive to collision rate and η_e .

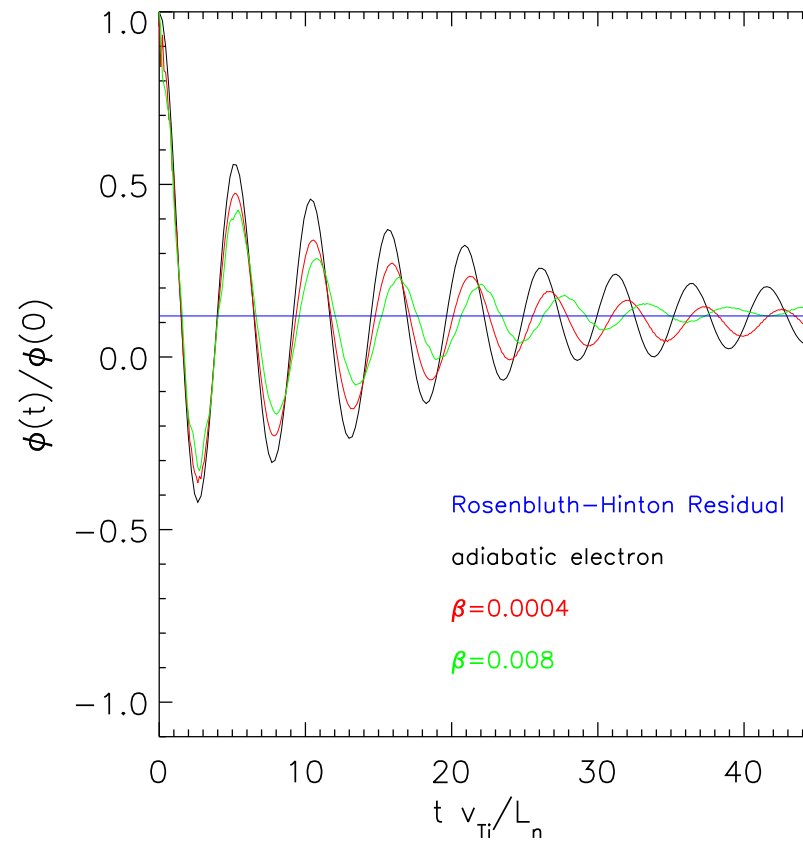
Effect of β on Ion Heat Transport



- DIII-D Cyclone Base Case, $R/L_T = 6.9$, $R/L_n = 2.2$, $q = 1.4$, $\hat{s} = 0.78$
- $m_i/m_e = 1837$, $NX = NY = 64$, $NZ = 32$, 4 Million per species
- $\nu_{ei}L_n/v_{Ti} = 0.136$
- Strong dependence of χ on β for low η_e and high collision rate
- Measured $\chi_i \sim 0.006 \chi_{adi}$

Linear Evolution of the Zonal Flow Little Changed

- Initial $\delta n_e = 0$, nonzero δn_i
- Keep only $n = 0$ mode



Summary and Future Work

- Solved the “High- β Problem” in electromagnetic simulation of Ion-Larmor-Radius scale turbulence.
- The 3-D flux-tube code has full electron dynamics, including
 - trapped and passing particles
 - parallel nonlinearity
 - Lorentzian collision operator
 - Realistic mass ratio
- Linearly benchmarked with continuum codes
- β -scan of ion heat flux. Details of collision rate and η_e needed.

Future Work

- Implement quasi-ballooning coordinates, general geometry within the Summit Framework.
- More efficient Ampere solver